Quantitative Analysis of Card-Gap Tests
The Reflected Wave Technique

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I. INTRODUCTION

One of the most useful methods of evaluating shock sensitivity of propellants and explosives is the card-gap shock attenuation test.[1-3] Because shock pressure is considered the most impartant parameter causing detonation in shock initiated explosives, conversion of gap thickness to shock pressure has been carried out at NOL[3] and Aerojet,[1,4] for various diameter card-gap tests using Plexiglas (or Lucite) as the attenuating medium.

It has been noted [1,5] that the shock pressure at the end of the attenuating gap is not the same as the shock pressure entering the test sample because of the "impedance-mismatch" at the interface between the Plexiglas attenuator and the test sample. The magnitude of this change depends on certain mechanical properties of the two media and is unknown since the data does not, in general, exist for most propellants and explosives. Without this knowledge card-gap test results remain qualitative.

An experimental-theoretical method, called the "Reflected Wave Technique" ("RWT") was developed[1] to determine transmitted shock pressures in card-gap test configurations without measurement or knowledge of the test-sample properties. The method uses the laws governing the modification of shock waves at the interface between the media and the experimental measurement of the velocities of the incident and reflected waves at the interface.

The main purpose of this investigation was to experimentally determine the accuracy of the "RWT". This was done by using the "RWT" to compute the shock pressure transmitted to water, carbon tetrachloride, 2024-T4 aluminum and C 1018 cold rolled steel using various diameter card-gap test configurations, and comparing the results with values of transmitted pressure obtained independently. The method was also applied to two other materials (simulated propellant[a] and #30 sand) for which the transmitted shock pressure could not be computed independently.

Since each application of the "RWT" requires the use of a streak camera, it was considered desirable to determine from the above results if an empirical correlation, independent of the test diameter, could be found between the incident and transmitted shock pressure for each Plexiglas-acceptor pair. Such a relation would save considerable time in allowing subsequent determination of transmitted pressure without further applications of the "RWT". In addition, application of the "RWT" provides pressure-particle velocity data for each material tested. Since this represents a new and relatively simple method of Hugoniot determination, the accuracy of the results were evaluated by comparison with values from the literature.

In this investigation, a series of framing camera studies were made in order to determine if a definite identification of the incident, reflected, and (for transparent acceptors) transmitted shock waves could be made. Also, observations were made to help determine to what extent the Plexiglas is altered by, or made opaque by, the prior passage of the incident shock.

[a] Polyurethane, aluminum and potassium chloride.

II. EXPERIMENTAL

Figure 1a is a schematic of the general experimental set-up used to determine the velocities of the incident and reflected waves. The relay lens was used to obtain an overall magnification of about 1 and was aligned with the streak camera lens by mounting it on an optical bench rigidly attached to the camera chassis. The distance between the lenses was about 48". The event, which was about 6' from the relay lens (approximately 33" from the armor glass at the end of the porthole), was mounted on a steel stand such that the Plexiglas-sample interface was near the optical axis. With this arrangement a field of view (on the vertical axis) of about 1", at the event, was obtained. Backlighting was provided by an argon bomb that consisted of a $3\frac{1}{2}$" diameter by 7" long quart ice-cream container with a slab of composition C-4 high explosive at one end and a translucent covering of Saran wrap and vellum paper at the other end. The bomb was taped to a stand so that its axis was on the optical axis of the system and was placed from 13-15" behind the event. Figures 1b and 1c are details of the two types of events used in this program. The first shows the card-gap test configuration used for solid samples while the other shows the equivalent test set-up used for liquid samples (i.e. the "aquarium" method[1].) To eliminate the distortion of the light from the argon bomb by the curved surfaces of the Plexiglas column, narrow parallel flats were machined and polished along opposite sides of all the columns. In each test the length to diameter ratio of the tetryl donor was kept constant at a value of 2. The tetryl density varied from 1.5 - 1.6 g/cm^3. For the solid tests the acceptor diameter was kept equal to the column diameter while the sample height was always 2 inches.

A high-speed continuous writing streak camera was used for all shock pressure measurement tests. In order to make the set-up depicted in Figure 1a practical, a f/2.5 lens with a focal length of 7" was used in the camera. The relay lens, with an aperture of f/6, had a focal length of 24". The smallest available slit (0.004 in. wide) was used to make the shock front image as sharp as possible. In order to help minimize computation errors a turbine speed of approximately 2000 rps was used (writing rate = 2.9 mm/µsec) which gave a streak at an angle of about 45° to the film. For most of the acceptor materials, tests were conducted with columns of $\frac{1}{2}$", 1", $1\frac{1}{2}$", and 2" diameter and lengths of $\frac{1}{2}$", 1", $1\frac{1}{2}$", and 2". The slit of the streak camera restricts the field of view to the flattened portion of these columns.

The streak-camera film record produced for each test was reduced by reading the films with a Gaertner microcomparator. The data was then numerically differentiated[1] to give a velocity at the film plane. To obtain real values of shock velocity this data was multiplied by the ratio of the magnification and time factors for each test.

The event (test set-up), streak camera, film development procedure, microcomparator, and calculation methods may all be considered as sources of systematic and random error in the experimental determination of shock velocity. Where possible, procedural refinement and/or changes were adopted in an attempt to minimize error. The estimated overall error in velocity was about 3.5%. In addition, the error in the determination of shock pressure is always greater than in the determination of shock velocity because of the relationship between them. The average error in determining shock pressure was computed to be about 13%.

A high speed framing camera was used for the qualitative investigations of the program. The test set-up was similar to that depicted in Figures 1a - 1c except that no relay lens was used. A camera speed of about 4000 rps was used to obtain 25 frames at a framing rate of about 980,000 frames per second. At this speed the shock wave could be followed at about 1.05 µsec intervals.

III. THEORETICAL

The basic laws that govern the modification of a shock wave passing through the boundary between two media may be stated verbally as: "shock pressure and particle velocity must remain continuous across the boundary" [1,2, 6-8] or:

$$P_t = P_i \pm P_r \qquad \text{and:} \tag{1}$$

$$u_t = u_i \mp u_r \tag{2}$$

where P is shock pressure (kbar), u is particle velocity (mm/μsec) and the subscripts t, i and r refer to the transmitted, incident, and reflected waves respectively. The sign to be used in equation 1 is determined by the "impedance mismatch" between the media through which the incident and transmitted waves pass. If $\rho_t U_t > \rho_i U_i$ (ρ is the initial (unshocked) density (gm/cm^3) and U is shock velocity (mm/μsec)) the plus (+) sign applies and if $\rho_t U_t < \rho_i U_i$ the minus (-) sign applies. For a given case, the opposite sign is used in equation 2.

The shock pressure transmitted to a test sample can be computed by combining equation 1 with the well known hydrodynamic relation:[b]

$$P = 10\rho U u \tag{3}$$

to give

$$P_t = 10\,\rho_i U_i u_i \pm 10\,\rho_r U_r u_r \tag{4}$$

In general, the incident wave passes through Plexiglas (i.e., the attenuator). If it is assumed that the incident wave does not greatly alter the Plexiglas,[c] the reflected wave may also be considered as passing through the same Plexiglas. In this case, (using subscript p to denote Plexiglas) $\rho_r = \rho_p$ and equation 4 becomes:

$$P_t = 10\,\rho_p (U_p u_p \pm U_r u_r) \tag{5}$$

The "Reflected Wave Technique" consists of an experimental measurement of U_p and U_r (from a streak camera record of the event),[d] computation of u_p and u_r from the previously measured equation of state of Plexiglas[1] (the reflected wave is assumed to be passing through unaltered Plexiglas) and application of equation 5 to give the shock pressure transmitted (P_t) to a test sample. It should be emphasized here that P_t is found without measurement or knowledge of the acceptor properties!

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[b] Eq's 1-3 are strictly applicable only to one-dimensional (planar) shocks. Even though the shocks produced in these tests (see Figure 2) are non-planar and therefore at least two-dimensional, the slit of the streak camera used to obtain the data restricts the field of view to such a small portion of the wave that the curvature may be ignored and the waves considered planar.

[c] This assumption means, in this case, that the density and equation of state of the medium through which the reflected wave passes is unchanged (or only slightly different) from Plexiglas.

[d] Although the basic equation used to derive equation 5, (i.e., equation 1) is strictly valid only at the interface, the measurements of U_p and U_r were made at some small distance (< 1mm) from the actual interface. This was done because during reflection the incident and reflected waves overlap (for a time equal to the incident wave pulse width) causing distortions of the streak record. These distortions can be seen near the interfaces of the records shown in Figure 3. The error introduced by measurements near, rather than at, the interface is considered negligible since attenuation of the waves over such small distances is negligible.

Hugoniot data for the acceptor may be computed from this result (i.e., P_t) and equation 2 with $u_i = u_p$.

$$u_t = u_p \mp u_r \tag{6}$$

Since both u_p and u_r were computed in applying the "RWT", u_t is found directly from equation 6. It is also possible to compute U_t from P_t and u_t by rearrangement of equation 3, if the density of the acceptor medium is known.

IV. RESULTS AND DISCUSSION

A. Framing Camera Studies

The results of 13 tests with a framing camera are summarized in Table I. A typical record is shown in Figure 2. Definite identification of the reflected wave was made in all but 3 of the tests. Further examination of the records showed that, except in one case, no visual damage (i.e., breakup or opacity) to the Plexiglas immediately behind the incident wave occurred. The two column diameters and various lengths provided a range of shock pressures (P_p) at the interface (7 to 70 Kbar) over which the above observation is valid. Although no definite conclusion can be made, these results help to support the assumption made in the development of the "RWT" that, "the incident wave does not greatly alter the Plexiglas."

The results in Table I show that the curvature of the waves for each diameter column was approximately constant. This indicates that curvature is a geometrical property independent of the total attenuation. The average, for $\frac{1}{2}$" diameter columns is 0.088 mm^{-1} while that for 2" diameter columns is 0.012 $mm.^{-1}$ In the worst case the maximum deviation from planarity for that portion of the shock wave viewed through the streak camera slit, is less than 0.001 mm. This result justifies the assumption made in the development of the "RWT" that the one-dimensional equations are applicable in this case.

No effects, pertinent to the results in Table I, of the acceptor material were noted. However, it was noted that for the liquid acceptors (water and CCl_4) the records were generally superior to the rest. This is probably due to the fact that the liquid surface (see Figure 1c) acts as a second blast shield and helps keep the gaseous detonation products which obscure the view, from following the incident wave too closely. In the dry shots, the lack of this added protection restricts the distance over which the reflected wave may be viewed since the gaseous products meet the reflected wave soon after reflection. This view is supported by the observation in Figures 3a-3d that the duration of the reflected wave is longer for the liquid acceptor (the scale of Figure 3a is ~ half the others) than for the dry acceptors. Since actual card-gap tests are always dry the shorter duration over which the reflected wave may be measured is more realistic in terms of what is to be expected. However, this imposes no special restriction on the "RWT" since the velocity of the reflected wave can be determined even for very short durations when a microcomparator is used for the measurements.

A number of the framing camera tests gave some unusual results. Two are of some interest here. In one the shock wave appeared self-luminous and also the argon bomb apparently did not light. No immediate explanation can be given but if the conditions under which the result occurred could be repeated, it might be possible to carry out the "RWT" without backlighting, and subsequent simplification of the test. In another test the apparent shock wave thickness is ~ 8.0 mm. This is unusually high (most shots average ~ 2.5 mm) and indicates a low velocity shock wave. This would imply that variations in the tetryl donor quality may exist. This variation has been noted by Cook[2] and is of concern since the reliability of the card-gap test depends on the reproducibility of shock pressure at a given attenuator distance which in turn depends directly on the quality of the donor used.

B. Streak Camera Studies

1. Accuracy of "RWT"

In order to check the accuracy of the "RWT" for the two liquid and two solid acceptor materials, the transmitted pressure (P_t) was computed and compared to the transmitted pressure found independently (P_t^*). The acceptors were: water, $\rho = 1.00$ g/cm^3; carbon tetrachloride, $\rho = 1.59$ g/cm^3; 2024-T4 aluminum, $\rho = 2.77$ g/cm^3; and C 1018 cold rolled steel, $\rho = 7.86$ g/cm^3.

Two statistical measures were applied to the data. They are

$$|\overline{PE}| = \text{average absolute \% error} = \sum_1^N \left|\frac{P_t^* - P_t}{P_t^*}\right| \times 100 / N$$

$$\overline{PE} = \text{average \% error} = \sum_1^N \left(\frac{P_t^* - P_t}{P_t^*}\right) \times 100 / N$$

The first measure will always be positive and describes the overall percentage accuracy of the method and is the main one considered. The second measure may be positive or negative and describes the overall percentage bias (or direction) of the method and determines if any consistent trends exist.

For the transparent acceptors (i.e., H_2O and CCl_4) the shock transmitted appeared on the streak camera record (see Figure 3a) and U_t was measured directly, u_t computed from the equation of state reported in the literature,[9] and P_t^* (the independent measure) computed from equation 3. This was then compared to the value computed by the "RWT". Since the impedance of water and CCl_4 are known to be less than that for Plexiglas the negative (-) sign was used in equation 5 for the "RWT" calculation. Because of the health hazard involved at the test site only a small amount of similar data for CCl_4 was found.

For those acceptor materials that are opaque (i.e., steel and aluminum), the streak camera record did not show the transmitted wave (see Figures 3b-d). In this case the shock pressure transmitted (the independent measurement) may be found by a graphical method which uses the known Hugoniot's of the acceptor and Plexiglas.[5,6,8-10] These values (P_{th}) are then compared to the ones computed by the "RWT". For both of these materials, the impedance is known to be higher than that for Plexiglas and the plus (+) sign was used in equation 5. In order to check the accuracy of using this "reflected Hugoniot" method as an independent measure of transmitted pressure when applied to the opaque acceptors, it was first applied to the transparent acceptors mentioned above, so that a comparison with the measured results could be made (P_{th} vs P_t^*).

The "RWT" was also applied to two other acceptor materials which are opaque but for which the Hugoniots are unknown. The materials were simulated propellant, $\rho = 1.65$ g/cm^3 and #30 sand, $\rho = 1.36$ g/cm^3. The impedances of these materials are unknown but since simulated propellant is a coherent solid more dense than Plexiglas, the plus (+) sign was used in equation 5 while the minus (-) sign was used for sand since it is an incoherent material not much more dense than Plexiglas ($\rho \simeq 1.2$ g/cm^3).

a. Transparent Acceptors

Table II and Figure 4 show the results of P_t vs P_t^* for 12 tests with a water acceptor. The line drawn in Figure 4 represents equality of pressures (i.e., 45° line) and the distribution of the data about this line is a measure of the applicability of the method. For this data $|\overline{PE}| = 11.3\%$ which indicates that the "RWT" can predict transmitted pressure with an overall error of < 12% (which is less than the average error in determining shock pressure) for this acceptor. For the same data $\overline{PE} = +4.1\%$ which indicates that, on the average, P_t falls slightly below P_t^*. Since $\overline{PE}$ is well within experimental error no bias of the data is indicated even though the three data points at high pressure are low. More data in this region is necessary to determine if any trends do exist and if the accuracy of the "RWT" falls off.

The "Hugoniot" method of determining shock pressure transmitted was applied to water and CCl_4 and provides data (P_{th}) also shown in Table II. This is used to evaluate the accuracy of the graphical method. The $|\overline{PE}|$ for this data (P_{th} vs P_t^*) is 37.1% and indicates that the "Hugoniot" technique predicts transmitted pressure with an overall error about 3 times as great as the "RWT" (and the experimental error). For the same data $\overline{PE} = 27.4\%$ which indicates that P_{th}, on the average, is somewhat above P_t^*. This figure is also not within experimental error and thus indicates a bias. It may be concluded that the "Hugoniot" method gives values of transmitted pressure that are $\sim$27% high.

Because of these differences, the reliability of using the "Hugoniot" method as an independent measure of transmitted pressure is in serious doubt. However, the bias in the data may be used to adjust the subsequent results for opaque materials to more realistic values.

b. Opaque Acceptors

The graphical method described was applied to the opaque acceptors, steel[11] and aluminum[11] and the results are shown in Table III (i.e., P_p vs P_{th}). Comparing the "RWT" method to this graphical method (P_t vs P_{th}) gives, $|\overline{PE}| = \overline{PE} = +21.8\%$. This poor agreement was at once resolved when the values of P_{th} were adjusted downward by the average bias (27.4%) computed above. These results (P_{tha}) are also shown in Table III, and the adjusted comparison (P_t vs P_{tha}) in Figure 5.

For this adjusted data, $|\overline{PE}| = 15.1\%$ which indicates that the "RWT" can predict transmitted pressure with an overall error of about 15% for these opaque acceptors. It should be noted that this value is somewhat conservative since the manipulation of the data necessary to establish realistic values of the independent transmitted pressure was done on an average basis. A more detailed analysis of the P_{th} vs P_t^* data might give a number of correction factors (instead of one) that would further improve the correlation seen in Figure 5. The $\overline{PE}$ for this data is +0.4% which is well within experimental error and indicates no bias.

From this discussion the results (P_t) of applying the "RWT" to simulated propellant and sand, shown in Table IV, may be considered to be accurate within 11-15%.

2. P_t vs P_p Correlation

From the data shown in Tables III and IV it is possible to determine if a simple relationship, independent of test diameter, exists between P_t and P_p for a given acceptor material. Figures 6-9 show the results of plotting P_p vs P_t for water and CCl_4, steel, aluminum, and simulated propellant and sand respectively. From the legend in each figure the diameter of the test used to find a particular point can be determined. The best-fit line drawn in each case was found by the least-squares method. They are:

water; $P_t = 0.837\ P_p - 4.387$ (7)

steel; $P_t = 1.083\ P_p + 6.18$ (8)

aluminum; $P_t = 1.221\ P_p + 1.36$ (9)

simulated propellant; $P_t = 1.050\ P_p + 1.81$ (10)

sand; $P_t = 0.9035\ P_p - 2.76$ (11)

Although in Figure 6 there is some spread of the water data in the low pressure region no trends with respect to test diameter are apparent. It may then be assumed that the spread is due to random deviations of the data. Comparing the data (less one very poor point) to equation 7 the $|\overline{FE}|^e$ is 23.2% which indicates the overall accuracy of using this relationship to predict P_t in water for a given P_p, independent of the diameter of the test, and without further streak camera records. Since there is only one data point for CCl_4 no correlation is possible..

The remaining correlations are somewhat better. For steel, aluminum, and simulated propellant the $|\overline{FE}|$ are 15.4%, 13.5%, and 7.7% respectively. Also no diameter trends are apparent. Since there are only two data points (at the same diameter) for sand, equation 11 passes through both and the accuracy of the correlation is unknown.

Although there is no specific reason to assume that the relationships in Figures 6-9 are linear (they could be quadratic, exponential, etc.) it is convenient to use the simplest form possible. The value of the $|\overline{FE}|$'s computed for the linear expressions indicate that this approach is warranted.

Since all the $|\overline{FE}|$'s except one are approximately within the average error in computing P_t ($\sim$13%) it may be concluded that a P_t vs P_p relationship does exist, and that it is independent of the diameter of the test. It is also interesting to note that the most accurate result ($|\overline{FE}| = 7.7\%$) was obtained with the material (simulated propellant) most closely resembling propellants and explosives.

3. Hugoniot Determination

As previously shown, equation 6 along with the result from the "RWT" can be used to compute one point on the Hugoniot of the acceptor. The results (P_t vs u_t) for water and CCl_4, steel, and aluminum appear in Table III and are plotted respectively in Figures 10-12 along with the Hugoniot curves from the literature.[6,9,11] It is evident that, except for CCl_4, the results are both inaccurate (considerable spread in the data) and biased (most points are below the line). It is difficult to explain these results but since the average error in computing P_t was shown to be $\sim$13% it is assumed that the scatter is due, at least in part, to errors in computing u_t. This was estimated to be from 13-40%, depending on the acceptor medium. In Figures 10-12 the computed errors in u_t are represented by the length of the horizontal lines through the points. Also, since the bias in computing P_t is only $\sim$+4% the bias in Figures 10-12 is assumed to be due mainly to a bias in computing u_t. It is not clear why this bias arises or what its magnitude would be.

From the foregoing results it may be concluded that further study and analysis, along with refinements in obtaining data, are needed before Hugoniot prediction by this method can be considered accurate and usable.

V. CONCLUSIONS

The major conclusions of this investigation are: (1) the "RWT" can be used to compute the shock pressure transmitted to a test specimen in card-gap test configurations with an accuracy of 11-15% without measurement or knowledge of the test sample properties; (2) the data from a few "RWT" tests may be used to determine a linear correlation for each acceptor material, between shock pressure transmitted and shock pressure in Plexiglas that is independent of the test diameter and; (3) Hugoniot prediction from the results of the "RWT" is not currently practical because of large errors in computing transmitted particle velocity.

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e In this case: $|\overline{FE}| = \sum_{1}^{N} \left| \frac{P_{t\,equation} - P_t}{P_{t\,equation}} \right| \times 100 / N$

References

1. Salzman, P.K., "Analysis of Shock Attenuation for 0.5 and 2.0 in. Diameter Card-Gap Sensitivity Tests", presented at the ARS Solid Propellant Rocket Conference at Waco, Texas, January 1962.

2. Cook, M.A. and Udy, L.L., "Calibrations of the Card-Gap Test", ARS Journal, 31, 52-57 (1961).

3. Jaffe, I., Beauregard, R.L. and Amster, A.B., "The Attenuation of Shock in Lucite", presented at Third ONR Symposium, Princeton, September 1960; also NAVORD Rep. 6876, U.S. Naval Ordnance Laboratory, White Oak, Silver Spring, Md., May 27, 1960.

4. Pesante, R.E., unpublished work.

5. Price, D. and Jaffe, I., "Large Scale Gap-Test: Interpretation of Results for Propellants", ARS Journal, 595, May 1961.

6. Walsh, J.M. and Rice, M.H., "Dynamic Compression of Liquids from Measurements on Strong Shock Waves", J. Chem. Phys., 26, No. 4, 815 (1957)

7. Lubanov, A.I., "Reflection and Refraction of Shock Waves at the Interface Between Two Media", J. Tech. Phys. (USSR) 9, 2035 (1958)

8. Rice, M.H., McQueen, R.G. and Walsh, J.M., Compression of Solids by Strong Shock Waves, Solid State Physics, Volume 6, Seitz and Turnbull (Editors), Academic Press Inc., 1958

9. Rice, M.H. and Walsh, J.M., "Equation of State of Water to 250 Kilobars", J. Chem. Phys., 26, No. 4, 824 (1957)

10. Al'tshuler, L.V., Kropnikov, K.K. and Brazhnik, M.I., "Dynamic Compressibilities of Metals Under Pressures From 400,000 to 4,000,000 Atmospheres", Soviet Physics JETP, 34(7), No. 4, 614 (1958).

11. Katz, S., Doran, D.G. and Curran, D.R., "Hugoniot Equation of State of Aluminum and Steel from Oblique Shock Measurement", Jour. Applied Phys., 30, No. 4, 568 (1959).

TABLE I

Framing Camera Studies

Acceptor	Column Diameter	Column Length	$\sim P_p$ (Kbar)	Curvature[a]	Waves Visible[b]	Breakup Visible[c]	Opacity[c]	Comments
Water $\rho = 1.00$ g/cm^3	1/2"	1/2"	15	0.092	I,-,T	None	None	Incident wave not sharp
	1/2"	1"	10	0.098	I,-,T	None	None	Too much light
	1/2"	1-1/2"	7	0.074	I,-,-	None	None	Too much light
	2"	1/2"	70	0.012	I,R,T	None	None	Wave self-luminous!
	2"	1"	45	0.012	I,R,T	None	None	Wave ~8.0mm thick
	2"	1-1/2"	25	0.014	I,R,T	None	None	Excellent results
	2"	1-1/2"	25	0.016	I,R,T	None	None	Color film
Steel $\rho = 7.86$ g/cm^3	1/2"	1"	10	-	I,R	None	None	Incident wave not sharp
	2"	1"	45	0.010	I,R	None	None	-
	2"	1-1/2"	25	0.012	I,R	Slight	Slight	-
CCl_4 $\rho = 1.59$ g/cm^3	2"	1-1/2"	25	0.0096	I,R,T	None	None	-
Sand $\rho = 1.36$ g/cm^3	2"	1"	45	0.011	I,R	None	None	-
Air $\rho = 0.00129$ g/cm^3	2"	2.2"	15	0.0095	I,R,-	None	None	Too much light

[a] Curvature = 1/r, r = radius of curvature of incident wave (mm^{-1})

[b] I = Incident Wave, R = Reflected Wave, T = Transmitted Wave (applicable for Water, CCl_4 and Air only)

[c] Directly behind incident wave

TABLE II

Transparent Acceptors

Acceptor	Column Diameter	P_p (Kbar)	P_t^* (Kbar)	P_t[a] (Kbar)	P_{th}[b] (Kbar)	u_t (mm/μsec.)
water	1"	10.1	3.65	2.76	7.4	0.477
$\rho = 1.00$ g/cm^3	1"	15.8	5.38	4.80	11.6	0.683
	1/2"	7.35	6.46	5.70	5.4	0.760
	1"	10.4	6.98	7.57	7.5	0.867
	2"	18.1	8.32	9.94	13.5	0.869
	1-1/2"	15.6	8.73	10.1	11.8	0.851
	1/2"	20.4	10.0	9.31	15.1	0.774
	2"	29.0	18.0	17.5	22.2	0.929
	1-1/2"	32.3	20.6	20.7	24.9	0.982
	1"	41.3	34.6	31.9	32.0	1.07
	1-1/2"	49.8	47.8	44.2	38.6	1.09
	2"	62.6	54.9	44.2	47.9	1.51
CCl_4	2"	22.3	20.8	-	19.3	-
$\rho = 1.59$ g/cm^3	1-1/2"	10.3	-	9.89	8.5	0.286

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[a] P_t vs. P_t^* : $|\overline{PE}| = 11.3\%$, $\overline{PE} = +4.05\%$

[b] P_{th} vs. P_t^* : $|\overline{PE}| = 37.1\%$, $\overline{PE} = -27.4\%$

TABLE III

Opaque Acceptors

Acceptor	Column Diameter	P_p (Kbar)	P_t (Kbar)	P_{th}[a] (Kbar)	P_{tha}[b] (Kbar)	u_t (mm./μsec.)
steel	1/2"	6.00	9.78	11.8	9.26	0.0589
$\rho = 7.86$ g/cm^3	1"	7.30	11.0	15.0	11.8	0.0948
	1/2"	7.67	12.7	15.4	12.1	0.0664
	1"	11.1	19.6	23.0	18.1	0.0580
	1-1/2"	12.5	22.9	25.4	19.9	0.0441
	1"	12.7	20.0	26.4	20.7	0.123
	1-1/2"	15.3	31.5	32.2	25.3	-
	1/2"	17.3	21.2	36.4	28.6	0.302
	1"	38.3	45.8	-	-	0.557
aluminum	1/2"	2.10	2.10	5.7	4.47	0.0658
$\rho = 2.77$ g/cm^3	1"	5.06	8.20	8.5	6.67	0.0526
	1/2"	7.57	11.4	12.7	9.97	0.0967
	1-1/2"	9.20	13.9	15.5	12.2	0.111
	1"	9.68	11.4	16.4	12.9	0.207
	1"	11.7	14.0	20.0	15.7	0.237
	1/2"	13.1	21.7	22.5	17.7	0.0972
	1-1/2"	18.1	20.6	30.6	24.0	0.357
	1-1/2"	29.7	38.8	51.6	40.5	0.387
	1"	33.2	41.0	58.0	45.5	0.476

[a] P_t vs. P_{th} : $|\overline{PE}|$ = 21.8%, $\overline{PE}$ = + 21.8%,

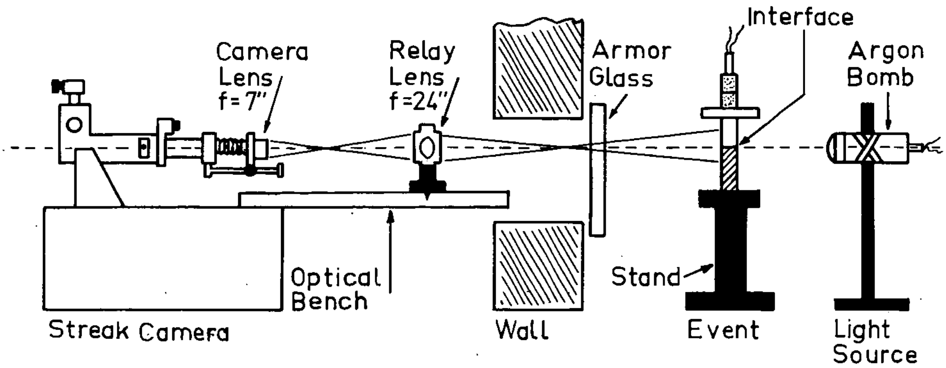
[b] P_t vs. P_{tha}: $|\overline{PE}|$ = 15.1%, $\overline{PE}$ = + 0.4%,

TABLE IV

Shock Pressure Transmitted

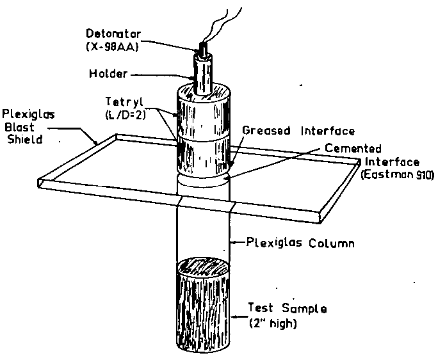
Opaque Acceptors; Unknown Hugoniots

Acceptor	Column Diameter	P_p (Kbar)	P_t (Kbar)
simulated	1"	10.9	10.9
propellant	1-1/2"	10.8	14.0
ρ= 1.648 g/cm^3	1"	12.6	15.5
	1-1/2"	14.6	20.8
	1-1/2"	23.8	27.4
	1"	43.6	45.2
	2"	56.8	58.9
	1-1/2"	110.5	119.6
sand	1"	6.60	3.20
ρ= 1.36 g/cm^3	1"	41.1	41.6



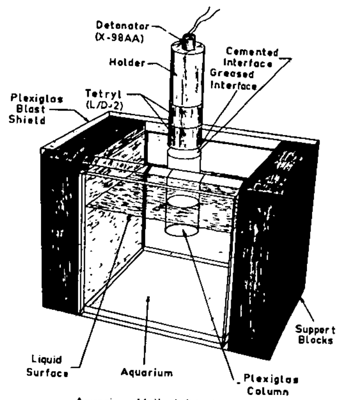
EXPERIMENTAL SET-UP

FIGURE 1a



Gap Test (Solids)

FIGURE 1b

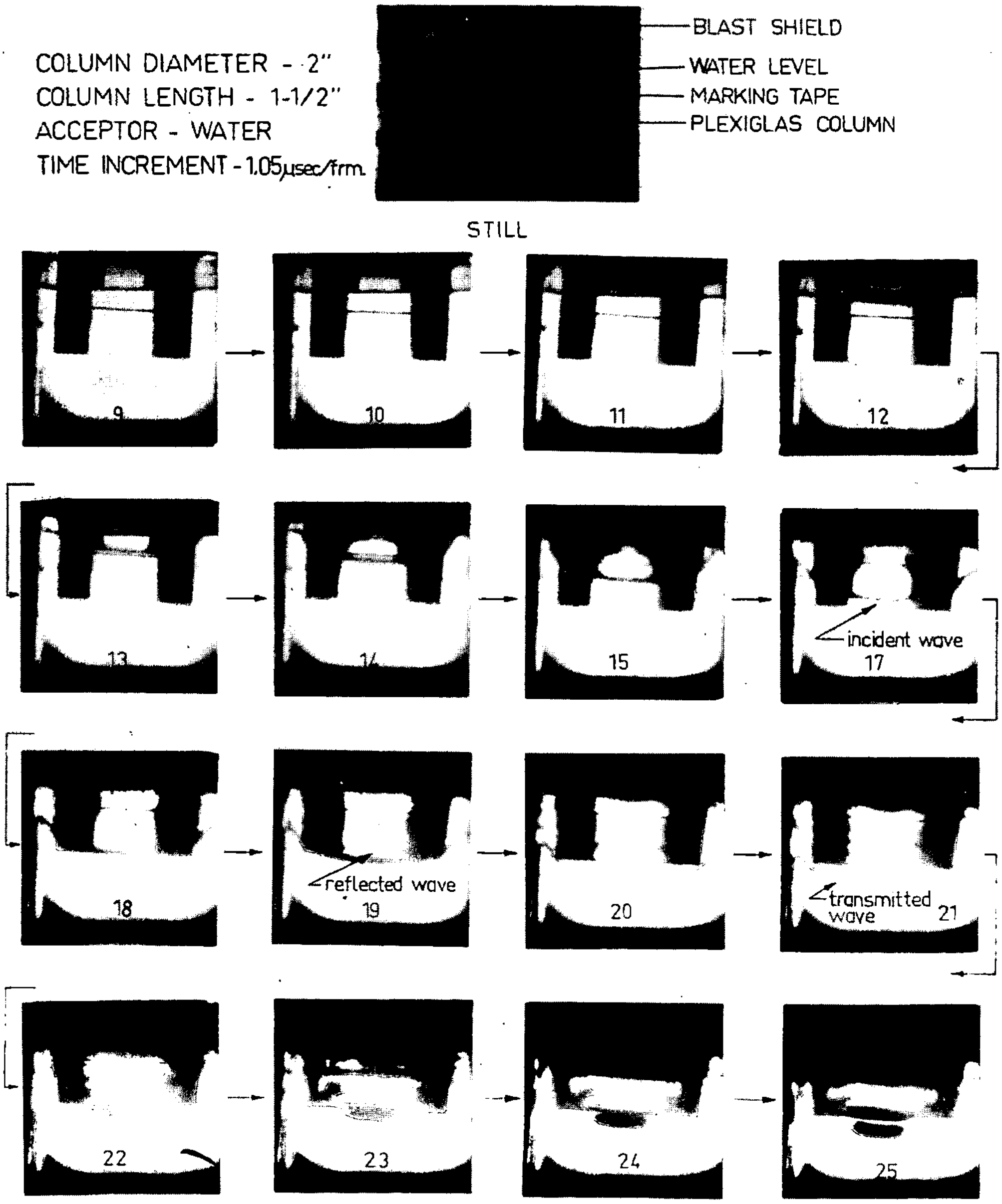


Aquarium Method (Liquids)

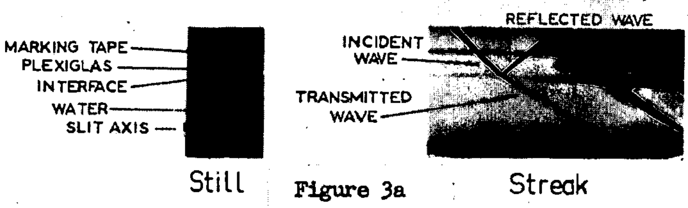
FIGURE 1c

Figure 2

FRAMING CAMERA STUDY

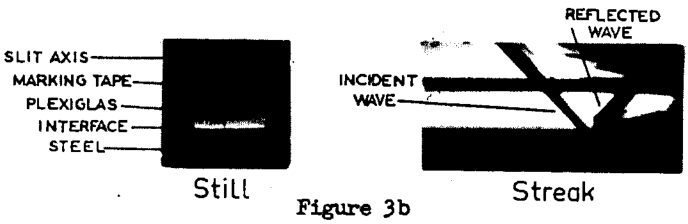


STREAK CAMERA STUDIES



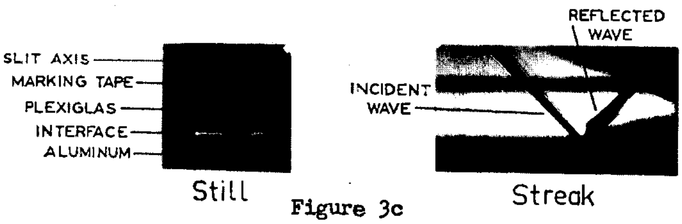
Column Diameter - 1"
Column Length - 1-1/2"
Acceptor - Water

Figure 3a



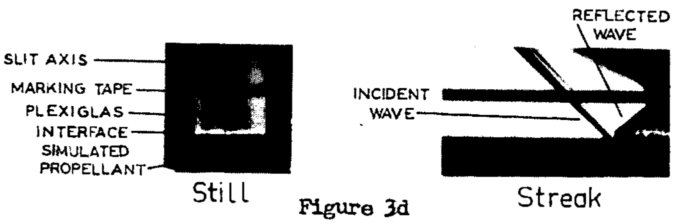
Column Diameter - 1-1/2"
Column Length - 2"
Acceptor - Steel

Figure 3b



Column Diameter - 1-1/2"
Column Length - 2"
Acceptor - Aluminum

Figure 3c



Column Diameter - 1"
Column Length - 1-1/2"
Acceptor - Simulated Propellant

Figure 3d

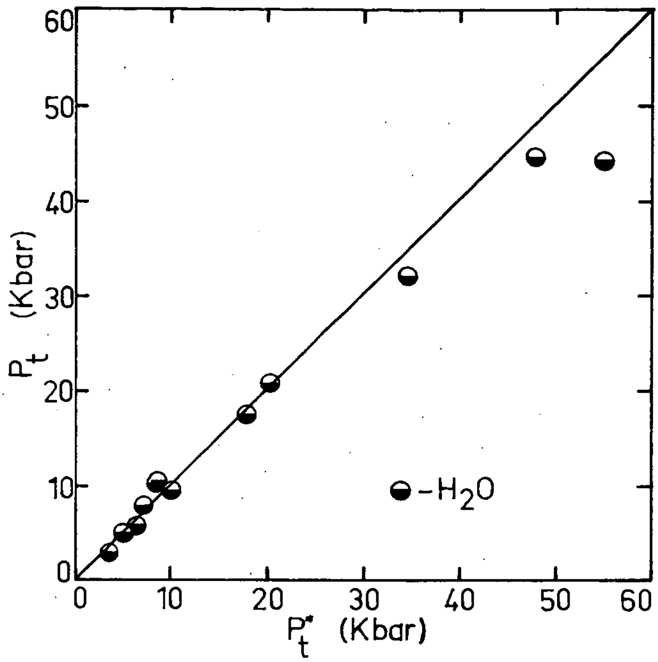


Figure 4 - Accuracy of "RWT", acceptor: water

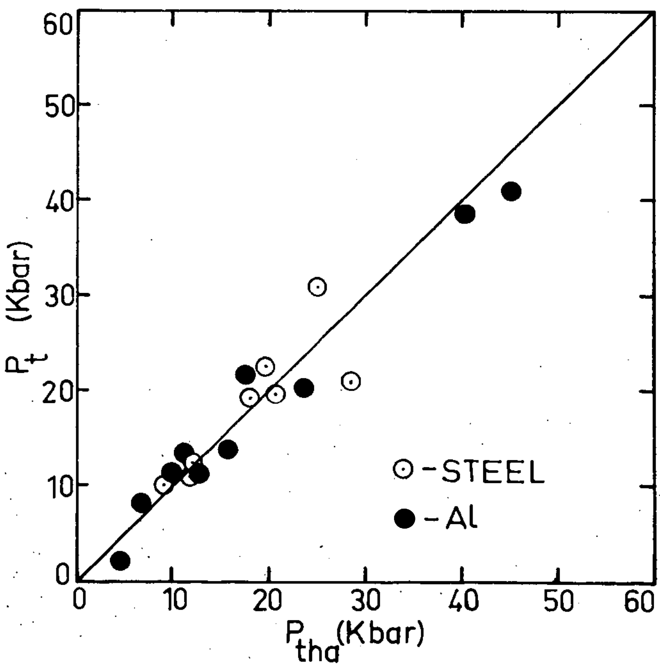


Figure 5 - Accuracy of "RWT", acceptors: steel, aluminum

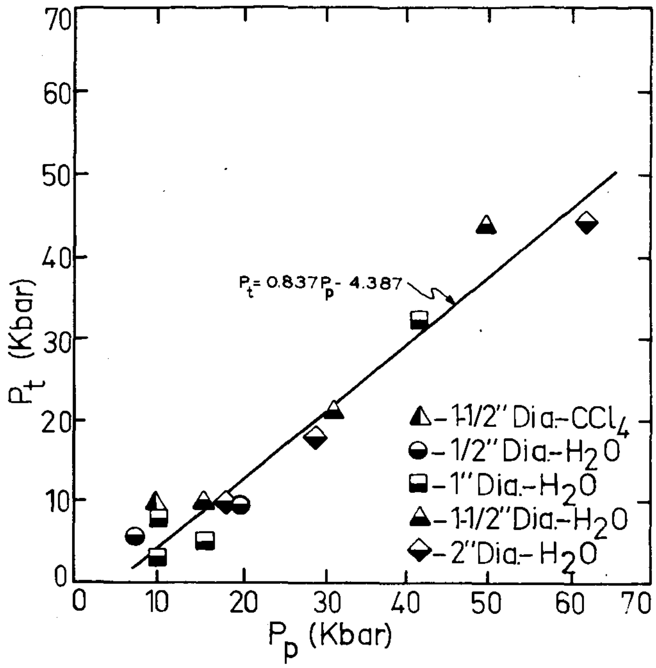


Figure 6 - P_t vs P_p Correlation, acceptors: water, CCl_4

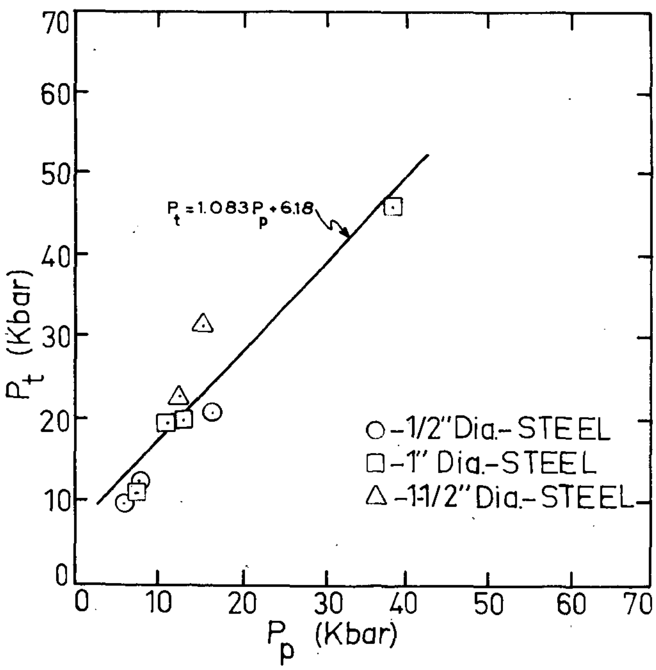


Figure 7 - P_t vs P_p Correlation, acceptor: steel

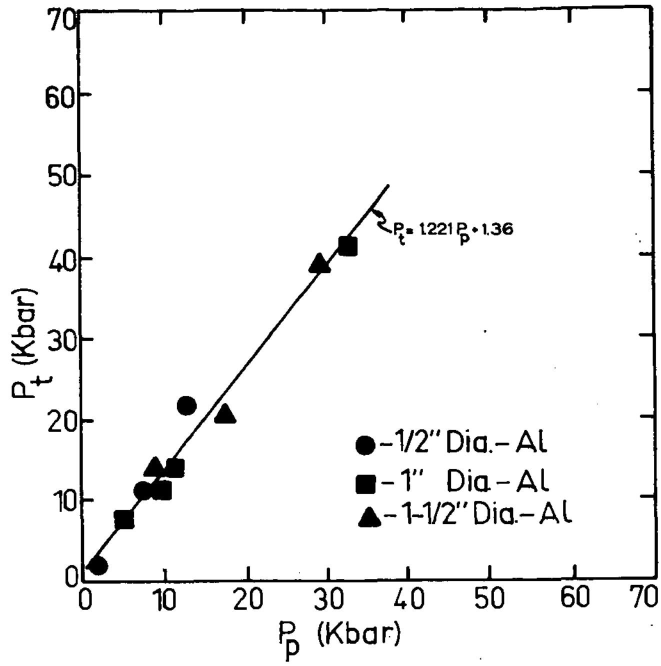


Figure 8 - P_t vs P_p Correlation, acceptor: aluminum

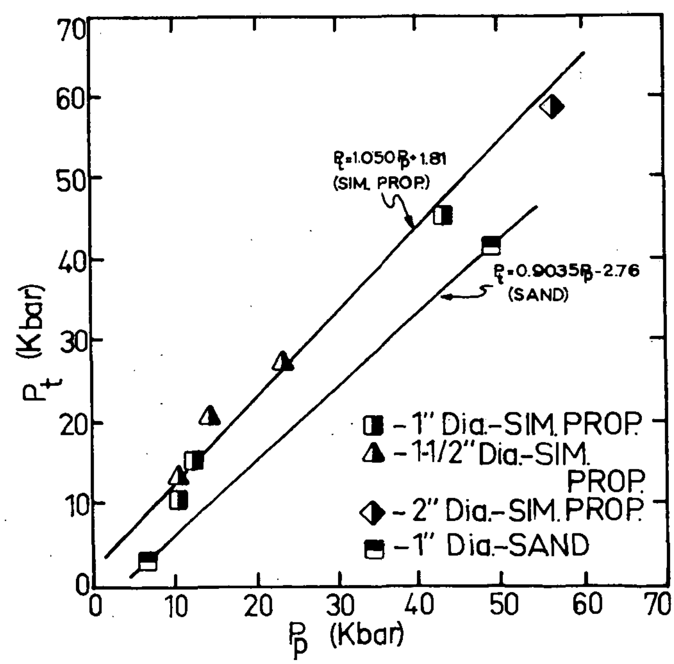


Figure 9 - P_t vs P_p Correlation, acceptors: simulated propellant, sand

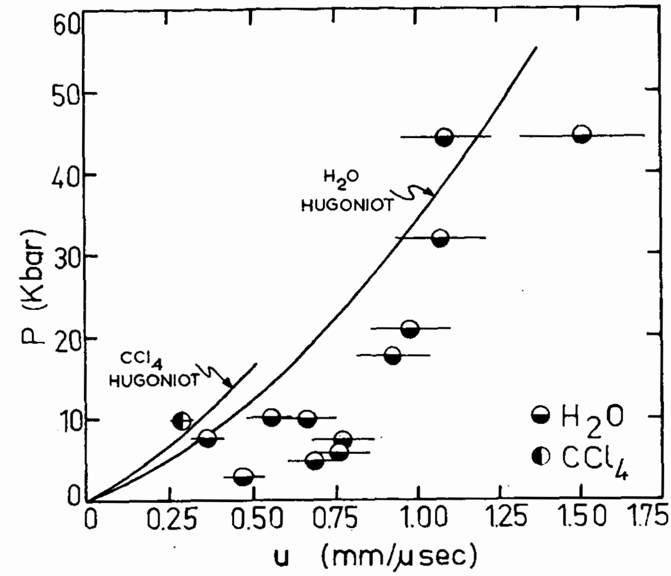


Figure 10 - Hugoniot Determination, water and CCl_4

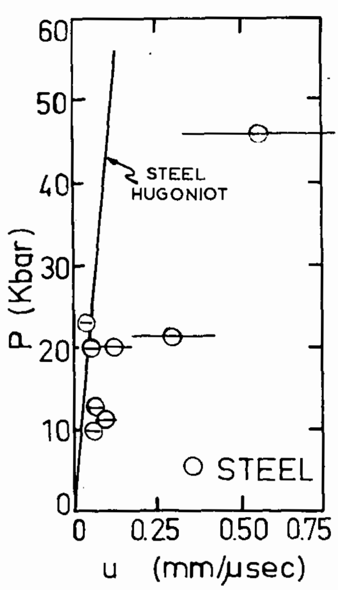


Figure 11
Hugoniot Determination, steel

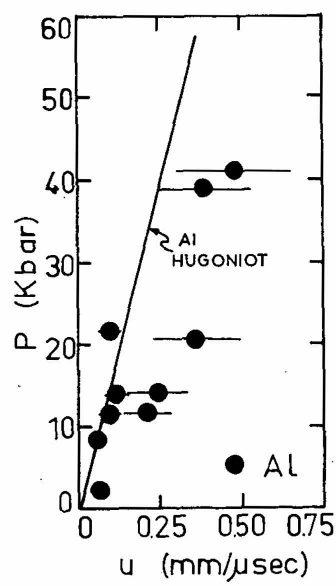


Figure 12
Hugoniot Determination, aluminum